P05

Simulation of Thermoelastic Instability and Sample-size Dependency of Dynamic Weakening in Friction Experiment

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Introduction

Scale dependency in friction is crucial in connecting small-scale lab-experimental studies and large-scale natural fault hosting large earthquakes. Since experiments by Tsutsumi and Shimamoto (1997), dynamic weakening in rock friction has been intensively studied in laboratory experiments for millimeter- to centimeter-scale samples of variety of rocks (e.g., Di Toro et al., 2011), and it has been revealed that the rock friction dramatically decreases at coseismic slip rate (~ 0.1 m/s) at which frictional heating becomes important. The weakening is primarily driven by temperature rise T on the sliding surface (e.g., Yao et al., 2016). Yamashita et al. (2015) conducted friction experiments for meter-scale samples and discovered that the dynamic weakening takes place at a smaller slip rate (~ 0.01 m/s), arguing that heterogeneity in the normal stress σ on the frictional surface causes concentration of frictional power and local activation of the dynamic weakening. Recently, Noda (2023) considered a mechanism called thermoelastic instability (TEI, e.g., Barber, 1967; Dow and Burton, 1972) and pointed out that the heterogeneity spontaneously grows at a higher slip rate V than the critical value V_{cr}, which is inversely proportional to the wavelength of perturbation and thus to the sample size. In the present study, TEI is simulated with a spectral method, and possibility of its operation in laboratory experiments is discussed quantitatively.

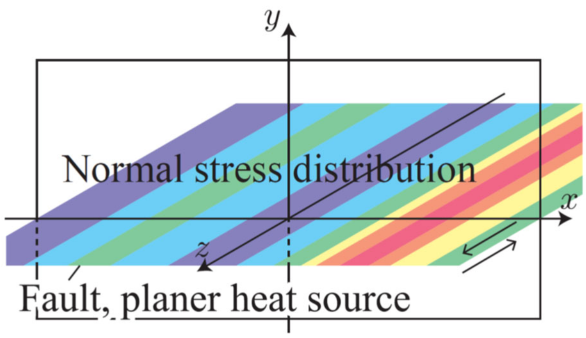

Fig. 1. A schematic diagram showing the system geometry considered here.

Methodology

Similarly to Noda (2023), a simple 2-dimensional quasistatic problem was considered, consisting of a planer sliding surface with antiplane slip embedded in an infinite linearly-thermoelastic medium (Fig. 1). Periodic boundaries were assumed with an interval of W along the sliding surface as approximation of the finite width of the sliding surface in experimental rock samples. Noda (2023) developed a numerical algorithm for calculation of evolving σ based on numerical approximation to spectral boundary integral equation method (SBIEM) by introducing memory variables. This method requires less numerical resources and does not suffer from growing memory needed in temporal convolution in SBIEM. The evolution of T was calculated with a spectral method with logarithmic wavenumber domain normal to the fault combined with an exponential time-differencing method (Noda and Lapusta, 2010). In addition, partial opening of the sliding surface was allowed, being calculated by solving the static elasticity at each timestep. A second-order embedded algorithm with controlling numerical error was adopted. The numerical solution was validated by comparing with a solution obtained by a standard SBIEM for a short simulation.

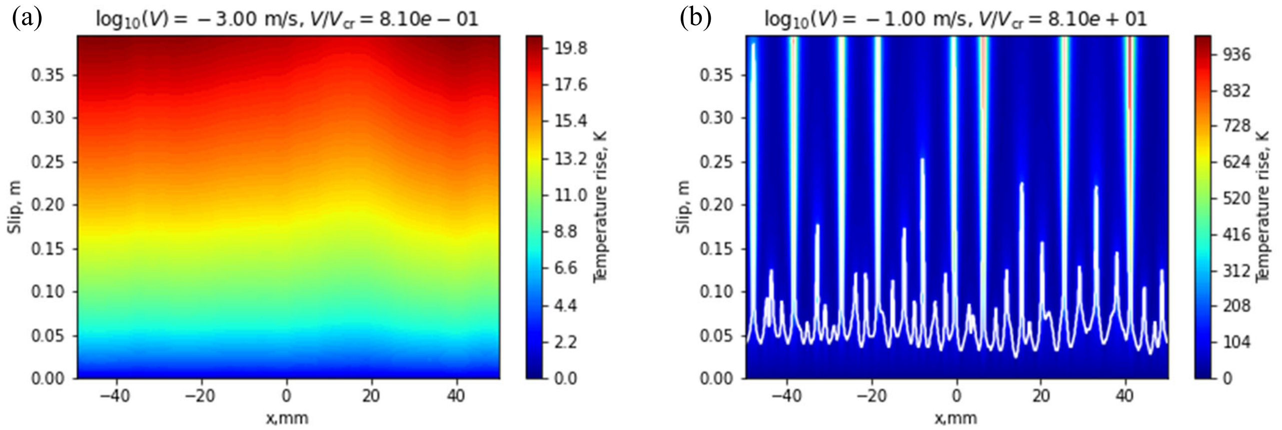

Fig. 2. Example simulations for evolution of T. (a) V = 1 mm/s for W = 0.1 m, showing almost uniform temperature rise. (b) V = 0.1 m for W = 0.1 m showing development of tiny hot spots in contact. White lines indicate timing of local opening of the sliding surface.

As for the friction coefficient f, a linear temperature-weakening model was assumed, based on previous experiments for dolerite (Noda et al., 2011),

$$f(T) = 0.75 - 0.4\,T/1000 \text{ [K]} \tag{1}$$

Simulations were conducted for conditions comparable to the experiments by Yamashita et al. (2015): thermoelastic properties of gabbro (Schön, 2015), spatially averaged σ of 6.7 MPa, V of 10^{-3} to 10^{-1} m/s, and the final slip of 0.4 m were adopted. To investigate the sample-size effect, W from 10^{-4} to 10^{-1} m were tested. The initial self-Affine perturbation in σ had Hurst exponent of 0 and 2.5% of the averaged value for the wavelength of 0.1 m.

Results and discussions

V_{cr} for the largest wavelength is 1.2 m/s for $W = 10^{-4}$ m and inversely proportional to W. If $V < V_{cr}$, almost uniform T (in space) and constant σ (in time) are realized, and the sample shows only modest weakening due to overall heating (Fig. 2a, 3). At such low slip rates, the sample-size effect was absent.

If V is only modestly larger than V_{cr}, sinusoidal growing perturbation modes appeared, but they did not lead to significant weakening because of restricted experimental duration.

At large enough V, the growing perturbation causes partial opening because the sliding surface cannot support tensile normal stress (white lines in Fig. 2b). Significant weakening takes place approximately at the onset of partial opening. In this regime, the sample-size effect appears such that a larger sample weakens at a smaller slip rate. In the case with $V/V_{cr} = 8.10 \times 10^1$ (Fig. 2b), The sliding surface is in contact only at small hot spots. This situation is similar to the flash heating, which is sometimes considered as a microscopic mechanism responsible for the dynamic weakening (e.g., Rice, 2006). The notable difference is that in the present study, the flash heating occurs as a consequence of macroscopic dynamics.

The present simulations indicate that TEI is indeed significant in laboratory experiments and probably responsible for the observed sample-size effect, illuminating the difficulty in direct application of the experimental results to natural phenomena of different length scale.

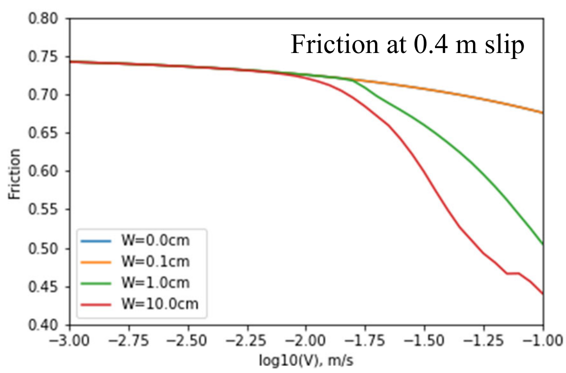

Fig. 3. Friction coefficient at 0.4 m slip for numerical friction experiments.